Continuous improvement planning through sustainability assessment of product-service systems

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Abstract: The paper presents a methodology for the integrated sustainability assessment of a product-service system lifecycle, with the purpose to support continuous improvement on the side both of the manufacturer and of the user. Its eight steps are an extension of ISO 14040 life cycle assessment and consider all three sustainability dimensions – economic, environmental and social – and a service perspective, using the service unit. A set of indicators for the three dimensions, aligned to the service unit concept, is proposed based on literature suggestions.

Keywords: Product Service Systems; sustainability assessment; life cycle; service unit; sustainability dimensions; environmental assessment; ISO 14040; economic assessment; social assessment; impact categories; sustainability indicators; Total Quality Management; continuous improvement.

1 Introduction

In 1987 the concept of sustainable development was defined by the Brundtland Commission as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (United Nations General Assembly, 1987). Then, the United Nations General Assembly (2005) categorized it into three relevant dimensions, which are economics, environment and society. Since its first definition, sustainability has represented the core topic of a research front. The research community is growingly interested in investigating synergies between Total Quality Management (TQM) and Sustainable Development (SD) from different perspectives and regarding its three dimensions (e.g. McAdam and Leonard, 2003; Tsai and Chou, 2009). From an operational perspective, TQM leads to better quality in products and processes and, consequently, to less production of waste and scraps, directly connected to emissions in the environment and to resource and energy consumption. Rework and waste have economic implications, named as "costs of poor quality" (Isaksson, 2005; Isaksson, 2006; Reed et al., 2000). Furthermore, a better product and process quality also achieves higher customer satisfaction (Reed et al., 2000). Service quality has been a huge area of research and is recognised as an imperative in manufacturing companies (Prakasha and Mohanty, 2012). In the last decades, due in part to the servitization trend in manufacturing, an increased attention was paid by manufacturing companies also in the quality of industrial services. The transition from selling products to integrating services into company's core offerings is characterized by a strong customer-oriented approach (Oliva and Kallenberg, 2003),

which enables companies to develop efficient and quality services (Aurich et al., 2010). A special case of servitization is the concept of Product-Service Systems (PSS) (Baines et al., 2009), defined as "*a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer's needs*" (Tukker and Tischner, 2006). Benefits associated to PSS concern costs reduction, decrease of relevant emissions and resource consumption and changes in social impacts, even without any physical modification on the products (Baines et al., 2009).
The current paper proposes a methodology to assess the sustainability impacts, regarding all sustainability dimensions during the lifecycle of a PSS solution, in particular focusing on its use life. Innovative elements, with respect to current assessment methodologies in literature, are mainly: the assessment of the three sustainability dimensions in parallel and the possibility to assess services, not only physical products, once system boundaries are set.
The adoption of the methodology has a particular potential use for the identification of improvement alternatives for product-service solutions at a concrete usage phase: this would enable a continuous improvement approach applied to PSSs.
The paper presents a literature review in Section 2, regarding the link between PSS, SD and current methods to assess sustainability. Section 3 introduces the methodology and its uses and gives a particular focus on the chosen indicators. Several scenarios of a case study demonstrating the methodology are illustrated in Section 4. Section 5 eventually presents some discussion on the results and suggestions for future research.

2 Literature Review

2.1 PSS types

The PSS concept is based on the idea that consumers do not specifically require a product, but the functionality that this product offers with its services. Facing this with a "green mindset" leads to higher degrees of freedom in the development of sustainable product-service solutions and of less impacting business models (Tukker and Tischner, 2006).
Literature agrees on a main classification of PSSs (Tukker, 2004):

1. Product-oriented PSS, where the focus is on the product complemented with additional services;
2. Use-oriented PSS, making the product available for use in different ways, usually owned by producers and shared by a number of users;
3. Result-oriented PSS, based on an agreed and desired outcome, without the involvement of specific products.

PSS may positively influence the three sustainability axes: (i) economic benefits come from the potential in differentiation and competitiveness of PSSs (especially against low cost economies), due to a more customized (Mont, 2004) and of higher quality product-services; (ii) PSSs allow a more intensive usage of products and a reduction of total production, thanks to the promotion of alternative uses of products, to the encouraged dematerialization of the offer (Mont, 2004; Ryan, 2000) and to the manufacturers' responsibility over the final disposal of produced goods, leading to less impacting product design and uses; (iii) for society, governments may release sustainability-boosting policies inspired by PSSs, and added services may create new job positions (having service activities a higher labour input per Euro than products (Stahel, 2000)). PSSs are also considered effective enablers to sustainability thanks to renting-sharing services of environmentally sound (and often expensive) products thus allowing to overthrow high price entry barriers (Tukker, 2004).

2.2 Sustainability Assessment Methodologies

Sustainability assessment methodologies in literature are numerous. Some propose theoretical approaches, others specific industrial cases. The majority of them focus on one specific sustainability dimension, within which only few impact categories are addressed. It is rare that these methodologies reach complete integration over the triple bottom line, even if many authors wish for it (Klöpffer, 2008; Rebitzer and Hunkeler, 2003; 2005).

The following paragraphs present the most relevant methodologies in literature for this work. Life Cycle Assessment and Material Input per Service Unit methodologies regard the environmental dimension; the following sections mention economic and social assessment approaches and, finally, some examples concerning their integration are illustrated.

2.2.1 Environmental Assessment

The most common environmental assessment technique is the Life Cycle Assessment, described in the International ISO 14040 standard (International Organization for Standardization, 1997).

ISO 14040 is characterized by a lifecycle perspective, which considers cradle-to-grave phases (raw materials, manufacturing, assembly, distribution, use, end-of-life) and is necessary to avoid shifting of environmental burdens from one lifecycle step to another (Finkbeiner et al., 2006). It serves both as a decision support tool to compare impacts of different techno-economic alternatives and as quantifier for improvement potentials under many environmental respects: climate change, stratospheric ozone depletion, smog creation, euthrophication, acidification and similar. In order to compare different product solutions, data are normalized on the functional unit, which describes and quantifies properties of the product, such as functionality, appearance, stability, durability, ease of maintenance, etc. (Weidema et al., 2004).

MIPS methodology (Material Input Per Service unit) was developed by the Wuppertal Institute for Climate, Environment and Energy (Lettenmeier, 2009; Ritthoff et al., 2002), in order to support the quantification of materials and energy needed to provide a service, considering the complete lifecycle of products constituting its physical bases and then expanding the evaluation to a wider service perspective through the concept of Service Unit. The latter is similar to the concept of Functional Unit, mentioned in LCA, but is more focused on the service delivered than on the physical product.

The perspective of this methodology is different from the conventional ones, which strive for less emissions and waste: if less materials and energy are used as input to the system, also the emitted output will be lighter. This encourages dematerialization of existing products and production processes thanks to the service perspective, which is consistent with the tendency of offering PSSs (Ryan, 2000), instead of simply selling physical goods.

2.2.2 Economic Assessment

Economic assessments in literature consider the lifecycle of the product-service, as the already mentioned environmental ones. The most popular indicators are the Life Cycle Cost (LCC - sum of all costs for a certain player related to the product-service), Net Present Value (NPV - algebraic sum of all discounted costs and revenues for a certain player), Profitability Index (value increase per investment) and Internal Rate of Return

(the discount rate which makes the NPV of a project equal to zero). The Payback Period (time for a project to repay for itself) is used as a complementary indicator with one of the above-mentioned ones, although not having a lifecycle perspective itself (Asiedu and Gu, 1998; Biezma and San Cristobal, 2006; Mao, 1970). The lifecycle perspective is used to avoid selecting an alternative with lower initial costs but higher operations and maintenance costs. Usage costs may be equal to many times the initial purchase or investment costs (Woodward, 1997).
Life Cycle Cost is the economic counterpart of the environmental LCA and its several uses may be: support in the choice of alternatives (Cole and Sterner, 2000; Woodward, 1997); selection of new approaches for maintenance and operations management (Frangopol et al., 1997; Karyagina et al., 1998; Utne et al., 2012); optimization of new product-services design (Asiedu and Gu, 1998; Curran et al., 2007) and triggering changes in current configurations of existing systems (Wang and Sivazlian, 1997).

2.2.3 Social Assessment

Although products and services have social consequences at all stages of their lifecycles, social burdens are still not extensively considered. There is still no widely accepted assessment approach and social consequences are difficult to quantify into flows related to the product-services (which is easier for financial and physical flows). Moreover, the type of information needed is more complex to obtain and deal with, as it has to do with the single company's conduct and its impact on stakeholders with very high site-specificity (Dreyer et al., 2006; Jørgensen et al., 2008). Unlike environmental assessment, where the so called Areas of Protection must be protected from undesired emissions or resource consumption, within society the controlled areas are not strictly "under protection from damage" but are those where improvement is possible and desirable (Dreyer et al., 2006; Grießhammer et al., 2006; Hauschild et al., 2008; Jørgensen et al., 2008). Some authors suggest that LCA can be used as a conceptual basis for social assessment, as it is a widely acknowledged methodology (Dreyer at al., 2006, 2010; Grießhammer et al., 2006; Hauschild et al., 2008; Klöpffer, 2008; Rebitzer and Hunkeler, 2005). The outcome of this adaptation is the SLCA (Social Life Cycle Assessment). SLCA is not conflicting with the principles of profitability and competitiveness in business, it is just a decision support tool to do business in a socially responsible manner (Dreyer et al., 2006). SLCA has a theoretical basis but has not yet practical implementations. Social impact categories are usually referring to principles expressed in the Universal Declaration of Human Rights, in SA8000 (Social Accountability International, 2008), in the Tripartite Declaration of Principles concerning Multinational Enterprises and Social Policies and in International Labour Organization conventions (Dreyer at al., 2006, 2010; Hauschild et al., 2008). Some examples of possible social impact categories are the following: avoidance of discrimination, child labour, forced labour, freedom of association and collective bargaining, physical working conditions, training and education of employees, health and safety of employees, job creation, support for local community development (Dreyer at al., 2006, 2010; Grießhammer et al., 2006; Hauschild et al., 2008).

2.2.4 Integration of Three Dimensions

Integration of the three dimensions into a unique assessment would allow a complete sustainability overview. In fact, changes in environmental impacts of a company cannot be applied if not profitable for the company and any environmental and economic development cannot be stable in the long run without a basis of social fairness. For this

reason, it is important to assess the three aspects of sustainability at the same time (Klöpffer, 2008). To reach a consistent approach it is essential that overlapping areas shared by more than one dimension are not counted twice (i.e. human health issues may be considered both social and environmental, or local economy development may be both belonging to economic and social spheres).
The integration of environmental and economic evaluation is relatively easy and already adopted by many examples in literature (Cooper et al., 2012; Edkunge and Råberg, 1998; Fesanghary et al., 2012; Hong et al., 2011) thanks to the common data input (such as the used materials and energy) and the quantitative nature of indicators (Grefrath et al., 2012; Rebitzer et al., 2003; Shapiro, 2001). Moreover they can both be drastically reduced through a proper design of product-services (Alting and Brøbeh Legart, 1995; Hunkeler and Rebitzer, 2003; Rebitzer et al., 2003; Züst and Caduff, 1997).
The inclusion of the social dimension into the integration of environmental and economic assessments leads to a Sustainability Life Cycle Assessment (Sustainability LCA) (Grießhammer et al., 2006). The biggest challenge for integration is the qualitative nature of most social indicators, which makes the assessment much dependent on decision makers' personal opinions.
Examples of integration of the three sustainability dimensions are Full Cost Accounting techniques (Klöpffer, 2003; Cole et al., 2000), which consist in the economic quantification of social and environmental impacts to be included into the economic assessment, resulting in only one indicator for a complete sustainability assessment. Similar approaches are the Cost-Benefit Analysis and the Cost Effectiveness Analysis (Weidema, 2006; Cellini and Kee, 2010). Both of the analyses weigh the total expected economic-environmental-social costs against the total benefits; the first by subtracting their monetized values, the latter by calculating the ratio of a cost over a non-monetary benefit.
These techniques have limited applications for two main reasons (Klöpffer, 2003): on one side, the assignment of a monetary value to social and environmental damages and benefits is not easy (and sometimes even repulsive); on the other side, since companies do not actually bear these costs directly (the society as a whole pays for them), they do not receive the necessary consideration.

3 Sustainability Impact Calculation Methodology

Trying to overcome the gaps present in existing methodologies, the Sustainability Impact Calculation Methodology pursues the integration of the three sustainability dimensions using, whenever possible, the same data for more than one dimension. Integration also includes the goal of achieving completeness in the assessment within each impact category. Figure 1 shows the eight steps of the methodology.

I. *Definition of goal and scope:* definition of the PSS, that can be of any type according to the classification of Tischner and Tukker (2006), as well as the target scenarios to be compared with and the assumptions and criticalities of the analysis.
II. *Definition of system boundaries:* flows to be considered and to be neglected must be chosen. Traditionally, system boundaries define which flows are accounted for: in particular, those energy, material or financial flows which cross the system boundaries are considered, *while others are neglected*. In the proposed methodology, system boundaries differ according to each sustainability dimension:

- Environment: traditional system boundaries, considering only those material and energy flows that cross them, as inputs (resource consumption) or as outputs (emissions).
- Economics: financial flows may either cross the system boundaries, or be completely internal to the system (those flows that are costs for a player and revenues for another). In traditional assessments, internal flows would not be considered; here they are considered because economic sustainability must be ensured for each player and not only for the system as a whole.
- Social: it includes all target stakeholders, impacted by the PSS lifecycle, both internal (employee, customers, suppliers) and external (local community).

III. *Definition of processes to be assessed and of the lifecycle phases.* The assessment is performed separately for each lifecycle phase, to keep track of critical results and to implement direct improvement actions. Eventually, contributions from different lifecycle phases are aggregated into the complete lifecycle assessment.

IV. *Definition of Service Unit*. The number of Service Units provided throughout the PSS lifecycle is the normalization basis of many indicators. It is not a new concept, since it was introduced in MIPS methodology (Ritthoff et al. (2002); Lettenmeier (2009)). To identify the proper Service Unit, it must be understood which is the performance that must be guaranteed to the customer. This is in line with the idea that, by adding more services to the same physical product, the total number of Service Units may increase, reducing the impacts per single Service Unit delivered. In this perspective, the methodology is suitable to analyze the impacts of different PSS solutions.

V. *Selection of indicators*. Impact categories and indicators must be selected according to the focus of the analysis and the data available. Depending on the chosen indicators, the allocation procedure, data needed and data quality requirements must be made clear at this moment, as it will affect data collection and assessment results.

VI. *Collection of data*. The basis for the integration of sustainability dimensions is built in this phase. The structure of the data collection itself allows for the same input data to be used for more dimensions, if this is reasonable. Using the suggested structure, risks of double counting are avoided. Ideal sources are internal to the company. If internal information is not available, external data from trustful sources may be taken (from certified databases, statistical bureaus, governments and university studies). It is important to get data in the needed units of measure.

VII. *Calculation of indicators values*. All the indicators in each dimension are computed for each lifecycle phase. Traceability must be ensured, to identify which impacts and lifecycle phases are most critical. Final values are presented both in an aggregated form (for a general overview of the PSS) and in a disaggregated one to identify the single criticalities to be improved.

VIII. *Analysis and reporting of results* include different activities such as (i) interpretation of aggregated / disaggregate results, (ii) identification of criticalities and (iii) sensitivity analyses. Moreover, reporting consists in presentations to company's decision makers and ideation of improvement actions.

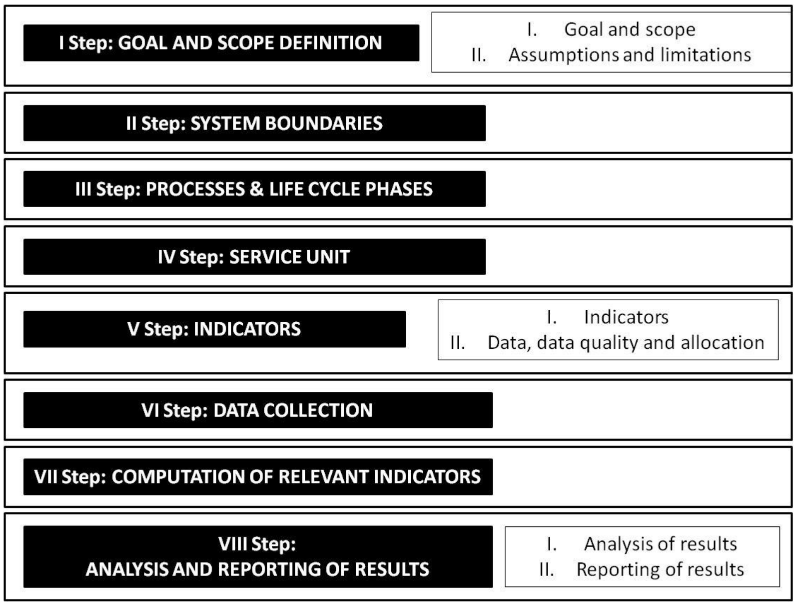

Figure 1 - Methodology Steps

The proposed methodology is based on ISO standard 14040 even if it is different in many aspects. It represents an extension in width (considering economic and social dimensions along with the environmental one) and depth (detailing the indicators to be used and not only the high level impact categories); and a change in mindset, as the assessment is on the service and not only the physical product. Moreover, the economic and social system boundaries are defined according to the relevant stakeholders, differently from the traditional configuration of system boundaries, considered only for the environment.
Possible uses of the methodology are four: (i) assessment of the sustainability impacts of a PSS; (ii) identification of most critical phases in the PSS lifecycle; (iii) comparison of different PSS alternatives; (iv) monitoring of long term changes of a PSS and its subsequent versions. Of course, consistency between uses and the selected impact categories and indicators must be ensured. All uses must be seen in the light of continuous improvement, since the assessment should be followed by the improvement of the triple bottom line performance.
The methodology has been implemented on MS™ Excel, chosen for its flexibility and popularity in use.

3.1 Classification of impact categories and indicators

Pursuing the objective of completeness, the methodology provides an indication of which impact categories and indicators to study. The proposed impact categories and indicators can be adapted or removed according to the specific case under assessment. The proposed indicators have been selected pursuing easiness in computation, relatedness to the concrete service and consistency with the approach philosophy (i.e. used as part of a decision making tool).

3.1.1 Environmental Indicators

Literature offers a wide set of environmental indicators, assessing either resource depletion or emissions during product use or evaluating product design. Table 1 reports the chosen indicators, grouped by perspective, with measure units and sources of respective formulas. Table 2 shows the indicators to be exploited for green marketing initiatives and to face stricter regulations from governmental norms, because they are easily understandable to the market and employees: these are a detailed analysis of the energy consumption and CO_2 emissions divided into energetic resources categories. Factors to compute their values are taken from literature.

Perspective	Impact category	Measure Unit	Source
Resource depletion	Abiotic Materials	Kg/S.U.	*Ritthoff et al. (2002); Lettenmeier (2009)*
	Biotic Materials		
	Soil Erosion		
	Water		
	Air		
Emissions	Acidification	SO_2 eq. Kg/S.U.	*Pehnt (2006)*
	Global Warming	CO_2 eq. Kg/S.U.	*WMO (2006)*
	Euthrophication	$(PO_4)^{3-}$ eq. Kg/S.U.	*Seppälä et al. (2004); Pehnt (2006)*
	Ozone Depletion	CFC-11 eq. Kg/S.U.	*WMO (2006)*
	Eco-toxicity	1.4 DCB eq. Kg/S.U.	*Huijbregts et al. (2000)*
	Human Toxicity	DALY/mg absorbed/S.U.	*Crettaz et al. (2002); Pennington et al. (2002)*
	Photochemical Oxidant Formation	C_2H_4 eq. Kg/S.U.	*Derwent et al. (1998)*
	PAN Creation	C_3H_6 eq. Kg/S.U.	
	Waste	Kg waste/S.U.	*Saur et al. (2000)*
Design variables	Recyclability	Rating 1-6	*Coulter et al. (1998)*
	Disassemblability	Rating 1-5	

Table 1 – Environmental Impact categories and Sources (S.U. stands for Service Unit)

CO_2 sources	**Measure Units**
CO_2 for fuel combustion	kg CO_2/S.U.
CO_2 for internal energy production	kg CO_2/S.U.
CO_2 for electricity	kg CO_2/S.U.
Total CO_2	kg CO_2/S.U.
Energy sources	**Measure Units**
Energy from renewable sources	MWh/S.U.
Electric energy from non renewable sources	MWh/S.U.
Other energy resources	kg/S.U.

Table 2 – CO_2 and Energy sources (S.U. stands for Service Unit)

3.1.2 Economic Indicators

Traditional indicators for costs and profits of a project are used for the economic assessment (Table 3). Two perspectives are monitored: the one of the company offering the product-service and the one of the user. With the double perspective, it is possible to obtain a first estimate of the cost-saving for the user and cost-rise for the company offering the product-services due to the addition of services to the products. This helps having an idea of the right pricing of services, in order to simultaneously ensure profitability for the company and cost-saving for the user. Economic sustainability is then granted for both players.

Indicator	Comments
Net Present Value for company	To have a general idea if it is profitable and how much.
Life Cycle Cost for company	It is a sum of all costs incurred by the company. Depending on the case, this sum can be discounted or not, according to the organization's preferences.
Total Cost of Ownership for the user	To understand the client's perspective and benchmark the company's offer to the competitors'. This can also be calculated both with discounted cash flows or non-discounted ones.
Payback Period	To evaluate the risks connected to the project.
Internal Rate of Return	To compare the return rate of the project to the desired one or to that of other products/services under development.

Table 3 – Economic indicators

3.1.3 Social Indicators

Social impact categories have been categorized with an innovative classification scheme. Three classes of categories are identified, containing different types of social indicators (Table 4):

(i) The first class includes fundamental issues, characterized by Boolean indicators: acceptable or non-acceptable.

(ii) The second class includes those impact categories that may influence economic and environmental impacts.

(iii) Social categories belonging to the third class are issues, which do not have a widely recognized optimal value, but they differ according to the single case and cultural context. Thus, these are assessed through an audit system.

Please note that what is intended in "health and safety of employees" (first class) is related to norms and standards and is expressible as a Boolean evaluation (respected or non-respected norms). "Physical work conditions" are instead included into a quantitative or semi-quantitative assessment (second class) and comprise more detailed indicators: fatalities and incidents, injuries, work-related diseases, etc.

Class	Categories
Fundamental Issues	Child labor
	Forced labor
	Health and safety of employees
	Corruption
	Respect for laws
	Degrading treatments
	Freedom of religion and opinion
Influencial on economics and environment	Allocation of profits
	Physical Work conditions
	Psychological and organizational work conditions
	Job satisfaction
Other issues	Gender discrimination
	Age discrimination
	Job for disabled
	Sustainable business partners
	Health and safety of users
	Intellectual property
	Ethics
	Local economy support
	Local community acceptance
	Freedom of expression

Table 4 – Social classes and impact categories

4. Case study

The company in the case study (later referred to as "company") is an agricultural machine and tractor manufacturer with a deep concern for sustainability issues. It has been selected for its trend to move towards different business models than traditional production-sale ones. They span from simple addition of services (such as maintenance, training and software), to Total Service Solutions. These new business models are ascribable to the concept of PSS. The possible benefits expected by the company are: reduction of emissions; waste and resource depletion; increase in farmers' life quality through a better management and automation on the field; increase in profits / reduction of cropping costs.

The case study aims at demonstrating all possible uses of the methodology. Section 4.1 focuses on the first three uses of the methodology, in the case of fixed OEE scenarios. It is helpful to understand the continuous improvement scenarios, successively shown in Section 4.2. In continuous improvement scenarios, OEE may vary, leading to the need of adapting the PSS solutions in order to cope with such variations. This last use, with its strongest link to the concept of continuous improvement, envisions the relevant role of monitoring the PSS solution in time.

4.1 Fixed OEE scenarios

The demonstration initially consisted in the application of the methodology on a use case regarding the assessment of three different scenarios (S1, S2 and S3). The application of each step is explained herein.

I Step

In S1 the machine speed is the one obtainable with the current service level; S2 includes speed enhancing services, resulting in a 10% speed increase; S3 corresponds to a full logistic service solution, which allows a 20% increase from the basic S1 speed. The three scenarios are all based on the same physical product, only the offered services differ. The case study wants to show how sustainability improvements may be reached through a sensible addition of services to a certain product. In particular S1 and S2 consider product-oriented PSSs, and S3 result-oriented PSSs. The OEE levels resulting from the three scenarios are: $OEE_1=0.87$; $OEE_2=0.93$; $OEE_3=0.98$ (where OEE = Performance level * Availability * Quality (Muchiri and Pintelon, 2008)).

II Step

System boundaries are, as defined by the methodology, different per each sustainability dimension. In particular, the environmental one considers both upstream resource depletion required for the production of materials and energy, and the emissions in the manufacturing and usage phases. Within the economic boundaries, the manufacturer and the user are considered both together and separately. Social boundaries include any person involved by the production or use of the PSS.

III Step

The company has visibility on three usage phases of its machines, therefore the lifecycle assessment will comprise four lifecycle phases including the manufacturing phase and the three usage phases, which are characterized by different performance levels, to keep into account the aging of machines. Since machines are made of good quality metals and materials, all components and materials are re-sold to developing countries and then recycled. From the company's perspective these cannot be further controlled and, according to the methodology, are out of the system boundaries.

IV Step

The Service Unit was fixed as 50 hectares of field harvested with a speed of 6.7 hectares per hour. Services added to the product can increase the speed of the machine, thus rising OEE. As a consequence, the number of Service Units provided in the lifecycle of the PSS becomes also higher.

V Step

Environmental indicators are reported in Tables 1 and 2; Economic and social indicators, respectively, in Tables 3 and 4.

VI and VII Steps have been performed at the company's premises, where relevant data were collected and indicators were computed using the Excel files. It was possible to use the company's internal data as sources. To reach a consistent integration, input data common to more than one dimension were carefully dealt with. The most critical phases resulting from this computations were the manufacturing phase for the consumption of resources and the fourth phase (3rd usage phase) for the emissions. The costs are highest in the second phase (1st usage phase) for the user and in the manufacturing phase for the company. The social burdens were fixed along the PSS lifecycle.

VIII Step

Results of the sustainability assessment have shown that, in the environmental sphere, each impact category reacts differently to the different scenarios. An example of differently impacted categories is shown in Table 5, where biotic materials, water consumption, acidification and terrestrial eutrophication potentials are decreasing, because the increased speed does not cause an addition in these emissions and the indicators are just affected by the growth in the number of Service Units (at the denominator of the computations). Soil depletion potential is not affected, because the lifecycle of the PSS does not need it; abiotic materials consumption is influenced to a limited extent, because the increase in number of Service Units balances the increase in materials needed for the increased speed (higher fuel consumption). Air consumption and global warming worsen their performances, because the increased fuel consumption uses more air for combustion and emits high quantities of CO_2 that cannot be balanced by the increase in the number of Service Units. An overall view of the behaviour of other indicators along the three scenarios is given in Fig. 2.

	Impact category	S1	S2	ΔS1-S2	S3	Δ S1-S3	Unit of measure
Improving	**Biotic Materials**	0.55	0.49	-9.1%	0.45	-16.7%	kg/S.U.
	Water	13 802.72	13 076.16	-5.3%	12 516.80	-9.3%	kg/S.U.
	Acidification	8.52	7.74	-9.1%	7.10	-16.7%	SO_2 eq kg/S.U.
	Terrestrial Euthrophication	1.44	1.31	-9.1%	1.20	-16.7%	$(PO_4)^{3-}$ eq kg/S.U.
Not-affected	**Soil**	0.00	0.00	-	0.00	-	kg/S.U.
	Abiotic Materials	1178.00	1141,00	-3.1%	1116.29	-5.2%	kg/S.U.
Worsening	**Air**	1 027.17	1 099.74	7.1%	1 174.70	14.4%	kg/S.U.
	Global Warming	860.53	937.15	8.9%	1 014.52	17.9%	CO_2 eq kg/S.U.

Table 5 - Differently impacted categories (S.U. stands for Service Unit)

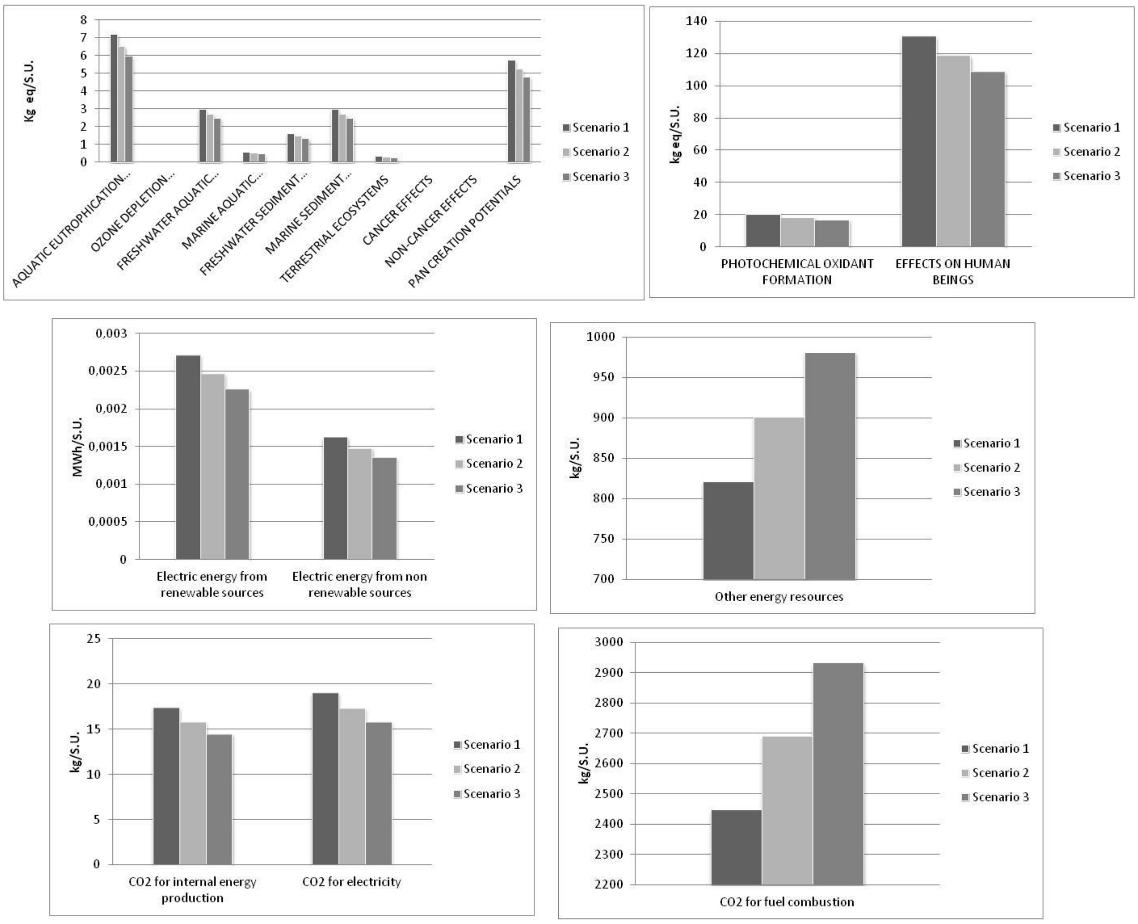

Figure 2 - Other environmental indicators

The economic dimension reports a steep decrease in lifecycle costs for the company (-9.1% in Scenario 2 and -16.7% in Scenario 3) and for the user (-7.4% and -13.4%). Lifecycle cost for the company comprised materials, service supply, energy, fuel, transportation, environmental certificates, labour costs; while users' costs included: investment cost, service fees and fuel costs. All of them are discounted considering the different years in which they are borne.

The social dimension does not record any quantifiable change in impacts to stakeholders. This is aligned with the expectations, since only marginal modification (for consumers, employees and local community) are introduced due to the additional services in the various scenarios. This example shows one of the main benefits of the integrated assessment methodology: it shows how changes benefit some indicators and worsen other aspects.

4.2 Continuous improvement scenarios

The methodology is particularly intended for its adoption in a continuous improvement context: thanks to the methodology, it is possible to monitor the sustainability performances of the PSS during its lifecycle, and to add new services or modify the existing ones whenever the performances are worse than expected. This belongs to the fourth use suggested in Section 3. It was not possible to validate it extensively, because it would require to monitor the PSS for a long period of time and the research had time constraints that are not comparable with the long life of a machine.

I Step

The new scope of the application is the following. Firstly, it is assumed that the customer chooses the basic service level, obtaining OEE_1. S1 machine speeds are, under ideal conditions, 3.4 ha/h during the first two usage phases, and 3.2 ha/h in the third phase. However, it could be supposed that, due to bad operating conditions, the actual speed provided by the machines decreases 10% more in the transitions to the second usage phase and again 10% more than the expected 6% to the third usage phase. Resulting in speeds equal to 3.06 ha/h and 2.57 ha/h. In these conditions, OEE variations occur: as a reaction, the customer may be willing to increase the service going to the next service level (i.e. from the service level in S1 to that of S2 and from S2 to that of S3), in order to rise OEE and speeds. To this end, it is estimated that the same percentage in speed increase is obtained as in the previous analysis presented in Section 4.1, by shifting from one service level to the other: 10% and 20% respectively by shifting from S1 service level to that of S2 and from S2 service level to that of S3.

Figure 3 presents a tree of possible paths that may be covered in such a scenario, where "Service level x" indicates the service level of Scenario Sx. In the second usage phase, it can be chosen to keep Service level 1, regardless of the poorer performance in speed terms, or to increase the service level to the next one in a "continuous improvement" approach, in order to gain a 10% increase in speed. Again in the third usage phase, it is possible to keep the service level as in the second usage phase or to shift it to the next level, as a reaction to the worse performance achieved.

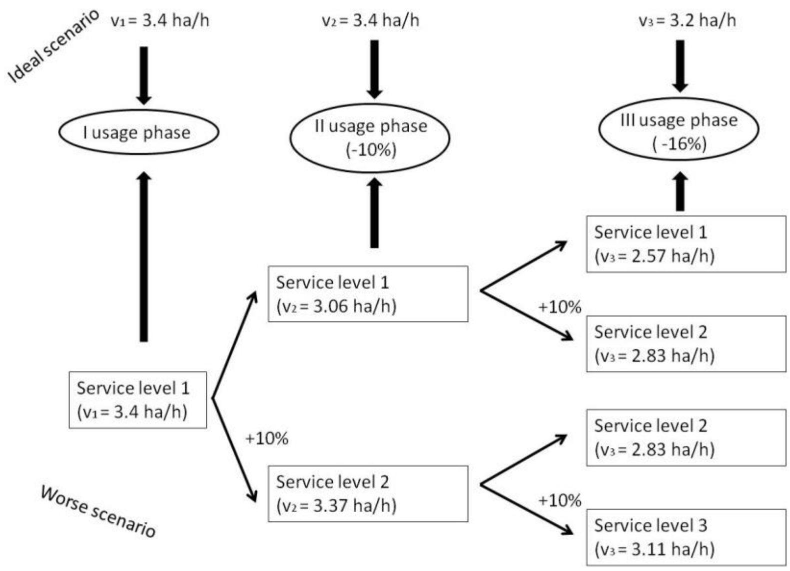

Figure 3 - Possible paths of continuous improvement

II, III and V Steps are the same as in Section 4.1. **IV and VI Steps** have been performed again to compute the new number of Service Units and to collect the new required data. For each of the four possible paths, it is possible to compute the lifecycle sustainability impacts through the methodology (**VII Step**).

VIII Step

Table 6 presents an example of a comparison of the impacts of the possible paths. The outcome shows that lower impacts in all environmental impact categories are achieved by: (i) reacting to the worse performance, with a higher service level (therefore with higher OEE); and (ii) reacting sooner. The behaviour of the other environmental indicators is shown in the histograms in Fig. 4. The economic dimension also shows lower costs both for the company and for the customer, recording a percentage cost decrease per Service Unit between 2% and 4% both for the company and for the user, in each transition from one path to the following one. The social dimension, as in the demonstration in Section 4.1, has only marginal changes that do not need to be shown in the results of this analysis.

	S1-S1-S1	**S1-S1-S2**	**S1-S2-S2**	**S1-S2-S3**	**Unit of measure**
Biotic Materials	0.55	0.53	0.51	0.50	kg/S.U.
Water	13 802.72	13 478.50	12 996.58	12 708.72	kg/S.U.
Acidification	8.52	8.32	8.02	7.84	SO_2 eq kg/S.U.
Terrestrial Eutrophication	1.44	1.40	1.35	1.32	$(PO_4)^{3-}$ eq kg/S.U.
Soil	0.00	0.00	0.00	0.00	kg/S.U.
Abiotic Materials	1178.00	1150.33	1109.2	1084.63	kg/S.U.
Air	1 027.17	1 003.04	967.18	945.75	kg/S.U.
Global Warming	860.53	840.31	810.27	792.32	CO_2 eq kg/S.U.

Table 6 - Impacts of different paths (S.U. stands for Service Unit)

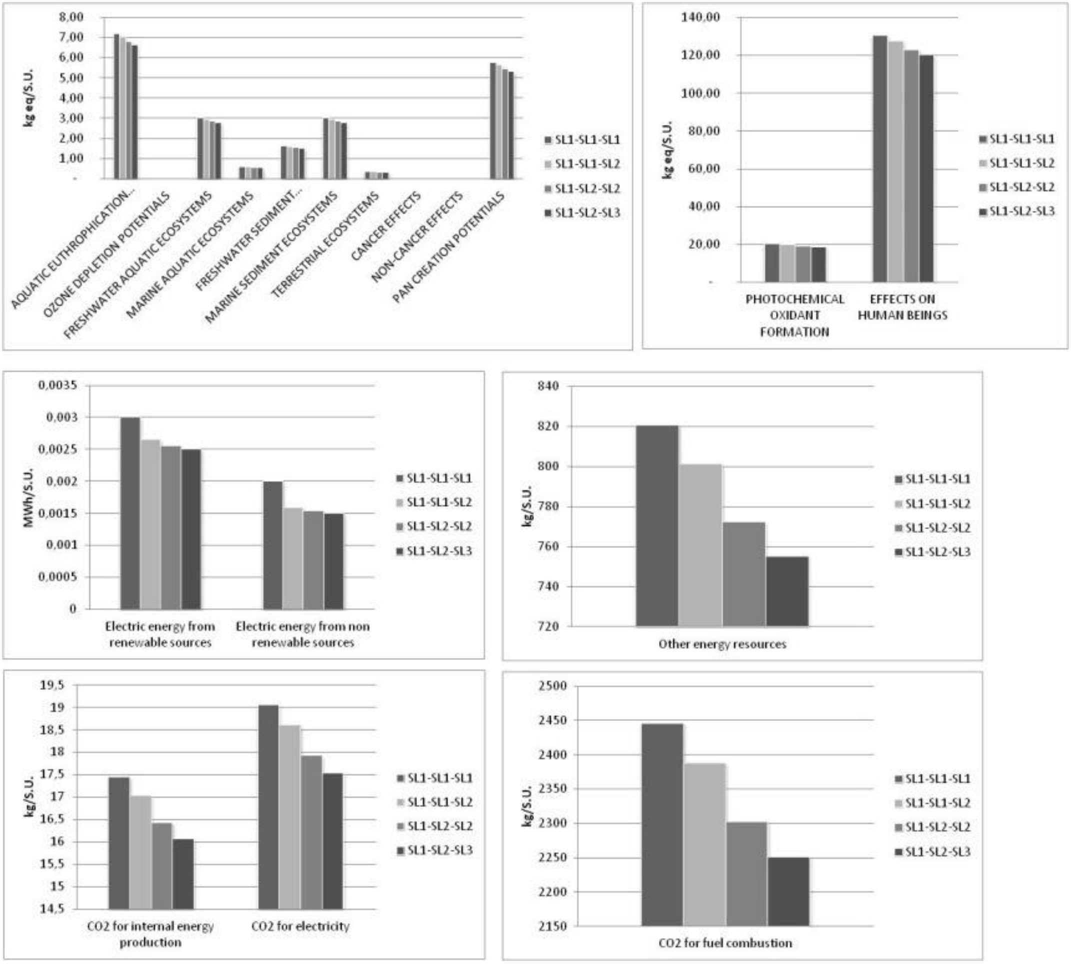

Figure 4 - Other environmental indicators

5. Discussion

The methodology fulfils the initial objectives and the case study confirms its main benefits: (i) avoiding local improvements of impact categories that result in worsened performances in others and the (ii) continuous improvement usage that provides an idea of the proper "reaction" to bad performances.

Lessons learnt from the case study related to activities critical for the methodology implementation are: (i) the setting of system boundaries is also a delicate matter, because they define which are the flows crossing them and those that are internal and must be accounted for; (ii)in the data collection phase, measure units must be clearly expressed and consistent with the "Service Unit" perspective; company representatives must be helped and guided in the definition of the proper Service Unit and in the collection of the appropriate data type. On the all, the implementation of the methodology, in order to be successful, must be characterized by requirements that are also common to TQM and sustainability driven organizational changes, such as management commitment, employee training, company culture.

The methodology can be improved with further research that may address the creation of analytical connections between the three sustainability dimensions: this would create an even more integrated sustainability assessment of PSS solutions. In particular, it would represent a great improvement, if the second class of social categories - which is the most quantitative among the social burdens and already shown factors impacting on the other two sustainability dimensions - is linked with mathematical expressions to the environmental and economic assessment. Moreover, the second class of social categories could be further investigated to express it "per Service Unit"; this would align it to the other dimensions of sustainability.

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